MODELLING TURBULENCE INTENSITIES INSIDE OFFSHORE WIND FARMS

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ABSTRACT. The turbulence in the marine boundary layer is generally low due to the low surface roughness of the sea. Inside a wind farm, however, it is influenced and often will be dominated by the additional turbulence generated by the wind turbine wakes. Thus, for design considerations, an accurate model is needed to calculate the turbulence intensity incident on a rotor inside a wind farm.

A semi-empirical model for calculating turbulence intensity inside offshore wind farms has been developed. The turbulence intensity profile in the wake of a wind turbine is taken from the wind speed deficit profile, which is from the axis-symmetric solution of the simplified Reynolds-Equation with the Ainslie wake model . Wake superposition, partial wake interference and wake meandering is taken into account to calculate the turbulence intensity incident on each rotor inside a wind farm for each wind direction and wind speed.

The model has been verified with measurements from different wind farms on land and offshore. A detailed comparison with measurements from the offshore wind farm Vindeby uses turbulence intensity profiles from double and quintable wake situations. The profiles from the model agree well with the Vindeby data.

The model is applied to the Middelgrunden offshore wind farm and compared with the mean turbulence intensities at the wind turbines for particular wind directions. It was found that the modelled turbulence intensities are higher than the measured ones. It is discussed if this is a shortcoming of the model or a measurement error. The model has been compared to the Frandsen model and it was found that the Frandsen model results in higher values.

1. INTRODUCTION

For the planning of wind farms, knowledge about the turbulence intensity at the wind turbines is important for the mechanical stability. Also for load calculations the turbulence incident on the rotor is needed. A wide range of approaches have been developed to calculate turbulence intensities behind wind turbines. An empirical formula for the rotor averaged turbulence intensity in the wake of a wind turbine were derived by Quarton and Ainslie [1]. Another way was gone by Frandsen [2], who developed a model for the design turbulence, which includes the characteristics of the material of the wind turbine in the calculation of turbulence intensity. The model is used in the IEC guidelines and allow a fast calculation of turbulence intensity in the wind farm. A semi-empirical model based on the wind speed profile in the wake was developed by Magnusson [3]. Gomez-Elvira [4] improved the CFD k-ε -model of Crespo for turbulence issues.

In offshore wind farms the increased turbulence inside the farms plays an important role. Due to the low ambient turbulence and there are large differences between ambient turbulence and wind farm turbulence. Therefore the forces on the wind turbines in a wake increase. To achieve good estimations of loads and high quality certification of wind farms for mechanical stability a reliable model is needed. Here we propose a new model to calculate the wind direction depending meteorological turbulence intensity inside a wind farm.

The following definition for turbulence intensity is used:

$$I = \frac{\sigma_u}{\bar{u}} \quad (1)$$

The mean wind speed $\bar{u}$ and the standard deviation σ_u are both measured at the same point and averaged for a period of 10 minutes.

The aim of the new model is to estimate the turbulence intensity at each wind turbine in a wind farm for any combination of wind speed and wind direction.

The wake turbulence has mainly two origins: Wind shear generated turbulence and rotor generated turbulence. The model describes the far wake, where the turbulence due to wind shear dominates. Additionally, the effect of shifting of the wake as a result of wind direction changes could induce fast changes of the wind speed for a static point in the wake [5],[6]).

In case of wind farm configuration the model has two fulfill two tasks: It calculates the turbulence intensity in the wake of one wind turbine (single wake) and superposes the wakes inside the wind farm (Multiple Wakes).

The paper is divided in the following parts: In section 2 we present the new model approach. First the calculation of the turbulence intensity profile behind one wind turbine (single wake) is described, followed by a short section about the model for the wind speed deficit profile. Then the treatment of superposition of wakes for wind farm configurations is described. In Section 3 the measurements for the validation of the model are presented. The model is compared to multiple wake situations from Vindeby wind farm in section 4. The validation with turbulence intensity measurements from Middelgrunden wind farm is done in section 5. In section 6 our new approach is compared to the model from Frandsen. Finally, conclusions are drawn in section 7.

2. Model Description

2.1. **Single Wake Model.** The turbulence intensity in the wake of one wind turbine is divided in two origins: the ambient turbulence intensity I_{amb} and the wake induced turbulence intensity I_{add}. The single wake model describes the turbulence intensity profile of the added turbulence intensity I_{add}. The added turbulence intensity profile is approximated as axis-symmetric.

The main effect for the generation of turbulence intensity has its origin in the wind speed gradient in the wake. The added turbulence is calculated from two contributions, a wind shear dependent and a diffusion dependent term:

$$I_{add}(r,x) = I_{shear}(\tilde{u}(r,x)) + I_{diff}(\tilde{u}(r,x)) \tag{2}$$

Both are based on the normalized wind deficit profile $\tilde{u}(r) = 1 - u(r)/u_0$, which describes the radial wind speed deficit profile at a lateral distance x from the upwind turbine and radial distance r from the center of the wake. u_0 means the incoming free wind speed.

2.1.1. *Wind shear dependent term.* Wind shear generated turbulence results from the wind speed gradient in the wake of a wind turbine and is therefore assumed to be proportional to the derivative of the wind speed profile. The derivation of the wind speed deficit profile calculated from the Ainslie model [7], as described in the following paragraph, is used.

$$I_{shear}(\tilde{u}(r,x)) = A I_{Lange}(x) \frac{\partial \tilde{u}(r,x)}{\partial (r/R)} \tag{3}$$

R is the rotor radius and A an empirical constant depending on the specific site and the wind turbine type. Here $I_{Lange}(r,x)$ is an approach from Lange [8]. The mean turbulence intensity in the wake is calculated with an empirical formula from the eddy viscosity of the Ainslie model.

2.1.2. *Turbulent diffusion dependent term.* Turbulent diffusion processes inside the wake and the meandering of the wake with wind direction changes, causes a smoothing of the turbulence intensity profile.

This is modelled following an approach from Magnusson [3], which is directly proportional to the wind speed deficit profile:

$$I_{diff}(\tilde{u}(r,x)) = B\tilde{u}(r,x) \tag{4}$$

where B is an empirical constant, which depends like A on the turbine type and the specific site.

2.1.3. *The Ainslie model.* Ainslie developed a model to simulate the stationary wind speed deficit profile in the wake of a wind turbine for a certain distance. It assumes an inertial wind speed profile at the end of the near wake (approx. 2 diameters behind the wind turbine), depending on the basic parameters: ambient wind speed u_0, ambient turbulence intensity I_{amb} and thrust coefficient of the rotor c_t. These profile is used as initial condition for a Navier-Stokes-Solver with eddy-viscosity closure, which than calculates the wind speed in the wake.

Lange used the eddy viscosity of the Ainslie-model to calculate the mean wake turbulence intensity created by the wind shear.

$$I_{Lange} = \varepsilon \frac{2.4}{\kappa u_0 z_H} \tag{5}$$

The variables are the von Karman constant κ (set to 0.4) and the height above the ground z_H.

2.2. **Superposition of the Wakes.** Inside a wind farm, the downwind turbines may be subject to multiple wakes on the rotor from the upwind turbines. The model has to superimpose the wakes from the upwind turbines. Also the development of the wake of the downwind turbine should be affected by the incoming turbulence intensity.

The superposition of the turbulence intensities in the wakes incident on the downwind wind turbine can be done in several ways. The best results are achieved, when the added turbulence intensities of the incident wake I_{add} are quadratically summed and added to the ambient turbulence intensity:

$$I = I_{amb} + \sqrt{\sum_{i=1}^{N} I_{add,i}^2} \tag{6}$$

The effect of the incoming turbulence intensity on a turbine inside a wind farm is taken into account by using the modelled turbulence intensity from the upwind wind turbines as ambient turbulence for the Ainslie model.

3. Measurements

3.1. **Vindeby.** The model is compared for offshore situation with double and quintable wake measurements from Vindeby offshore wind farm ([9]).

The Vindeby offshore wind farm is located off the northwestern coast of the island of Lolland, Denmark. The 11 Bonus 450 kW turbines are arranged in two rows as in fig. 1. The Bonus 450 have a rotor diameter of 37m and a hub height of 35m.([9])

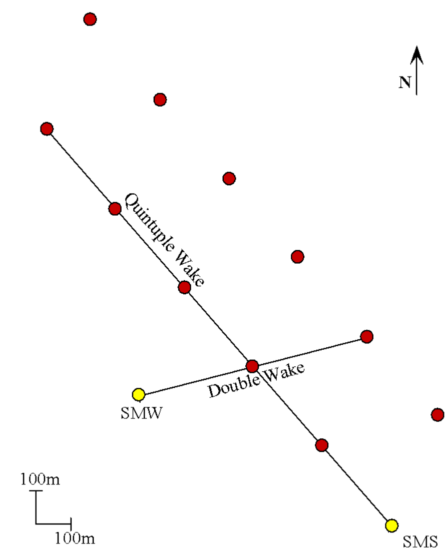


FIGURE 1. Layout of Vindeby wind farm

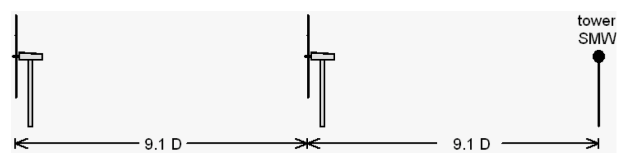


FIGURE 2. Vindeby wind farm: Double wake situation

Outside the wind farm the two measurement mast SMS and SMW are installed. For a wind direction of 75° double wake situation occurs for mast SMW while the mast SMS is in the free flow. A quintuple wake is measured at mast SMS at a wind direction of 320°, where SMW captures the free flow conditions. The setup along the axis of the wind turbines is shown in fig 2 for the double wake and fig 3 for the quintuple wake situation.

The horizontal turbulence intensity profiles were measured by a mast sited in the wake of a wind turbine.
Depending on the incoming wind direction, one section of the wake could be measured. For the average periods (normally ten minutes), the mean wind directions is used to estimate the measured part of the wake. Bin-averaging is used to get a stationary turbulence intensity profile.

The Vindeby Double and Quintuple turbulence intensity wake profiles are estimated from 1 min

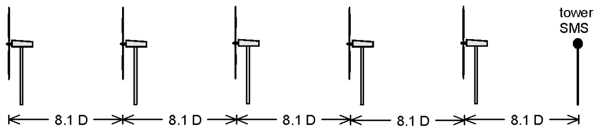


FIGURE 3. Vindeby wind farm: Quintuple wake situation

FIGURE 4. Layout of Middelgrunden wind farm with shown incoming wind direction

averaged data, concatenated to 10min averaged values, where a running average was used. A stationary turbulence intensity profile in the wake is derived by bin-averaging of 10 minutes averaged measurements to wind direction. Simultaneously, free stream conditions are measured by the second mast.

3.2. **Middelgrunden.** The wind farm model was also applied to measurements from the offshore wind farm Middelgrunden. Jorgensen ([10]) estimated rotor averaged turbulence intensities at the individual wind turbines from power fluctuation of the wind farm for particular wind directions. These turbulence intensities are compared with the model output.

Middelgrunden wind farm is an offshore wind farm located in the Oresund outside of Copenhagen. The wind farm consists of twenty turbines equally spaced with 2.4 diameters distance in a bow of approximately 12km fig. (4). The wind turbine type is BONUS 2MW with a rotor radius of 76m and a hub height of 64m.

The turbulence intensity values were estimated by Jørgensen [10] from the 10min averaged standard deviation of the electrical power with an empirical formula. The results are rotor averaged turbulence intensities for particular wind directions which are compared with the model.

4. COMPARISON OF THE MODEL WITH WAKE MEASUREMENTS

4.1. **Comparison to single wake measurements.** The inertial parameters A and B of the model were estimated by a fit of the model to a turbulence intensity profile from Nibe [11] onshore wind farm, described in [12]. The values are A=1.42 and B=0.54. They are used in the following.

4.2. **Vindeby double and quintuple wake.** The model was compared with the offshore situation at the Vindeby wind farm with double and quintuple wake measurements. The input wind speed for the measured wind profiles is from 8.5 to 10.5 m/s. The ambient turbulence intensity measured at the free standing meteorological mast and averaged over the wind direction, used for the wake profile, are for the double wake is 5.8% and for the quintuple wake 7.2%.

As can be seen in fig. 5(a) and 5(b) the modelled data agree well the measured turbulence intensity profiles. Both the maximum turbulence intensity and the shape are modelled accurately.

The shape of the measured turbulence profiles for double and quintuple wake situation are nearly symmetric, this results from a nearly uniform turbulence intensity over the wind direction due to a homogenous roughness of the surrounding water surface.

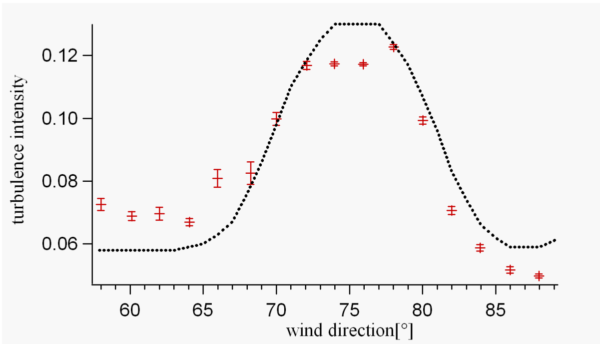
5. COMPARISON WITH MIDDELGRUNDEN WIND FARM

The estimated rotor averaged turbulence intensities at Middelgrunden for two different wind directions of 2° (I_{amb}=8.5%) and 10°(I_{amb}=8%) are compared with the rotor averaged turbulence intensities from the model as seen in fig. 6(a), 6(b).

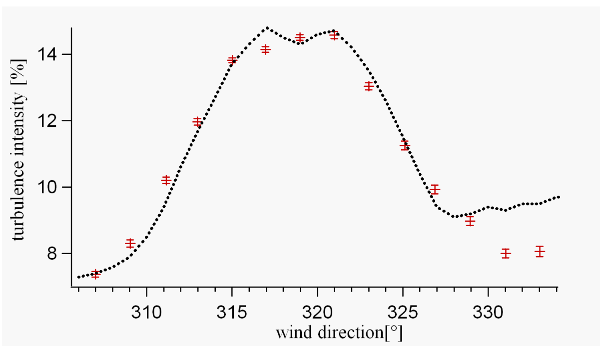
For the first wind turbine in a wake the turbulence intensity is modelled well. For the turbines further downwind, the model overestimates the turbulence intensity.

6. COMPARISON OF FRANDSEN AND OUR MODEL

Frandsen developed a model for fast calculation of the turbulence intensity inside the wind farm.

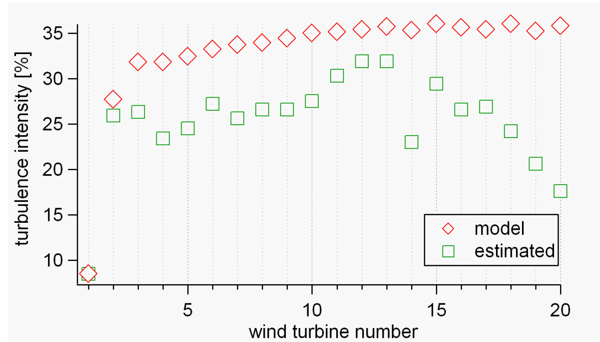


(a)

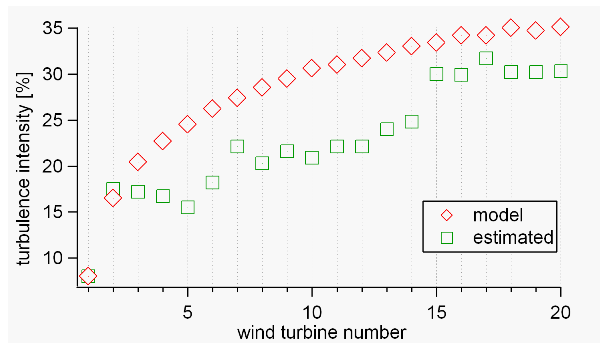


(b)

FIGURE 5. Measured and modelled horizontal turbulence intensity profile at Vindeby offshore wind farm from double (a) and quintuple (b) wake situation depending from incoming wind direction. The error bars mark the standard deviation from the bin-averaged turbulence intensities.



(a)



(b)

FIGURE 6. Rotor averaged turbulence intensities versus the wind turbines at Middelgrunden wind farm for the wind directions of: 2°(a) and 10°(b). The horizontal axis show the wind turbine number and the vertical axis the turbulence intensity.

The model is easy to handle and it is the industrial standard for calculation of the design turbulence intensity inside wind farms for safety requirements. For the calculation of the turbulence intensity at the turbines Frandsen differentiates between the ambient turbulence intensity and the wake turbulence intensity. Both parts of the turbulence incident on the rotor are weighted with the Wöhler exponent. The Wöhler exponent is a component depending value, which we set for the comparison of the meteorological turbulence intensity from our model to a value of m=2. For estimating loads with the design turbulence intensity this value is to low (for steel the value has to be m=4-5 and fibreglass m=10-12).

The model is compared to the turbulence intensity model from Frandsen for the Middelgrunden wind farm. The turbulence intensity at each turbine was estimated for a incoming wind speed of 8m/s. The ambient turbulence intensity was chosen to be 8.5 % for all wind directions.

The model calculates the turbulence intensity for each wind direction (1° steps). This is bin averaged for 12 sectors and weighted with the wind direction

TABLE 1. Farm configuration for Frandsen model

WEA	N	I'_0 used
1	1	No
2–5	2	No
6-15	2	Yes
16–19	2	No
20	1	No

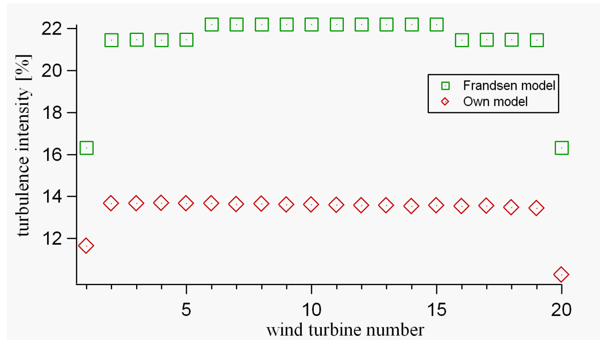


FIGURE 7. Comparison of Frandsen model with our new approach. The averaged turbulence intensity at each wind turbine is plotted against the wind turbine number.

distribution taken from the European Wind Atlas [13] (Site: Varløse; roughness class 0).

The Frandsen model was used according to the paper [2]. The probability of wake condition over all wind directions is set to p_w=0.06 for the calculation of turbulence intensity I_{eff}. The number of nearest wind turbines N for the affected wind turbine is given in table 1. There is also marked when the spatial average of turbulence in a wind farm I'_0 is used instead of the ambient turbulence intensity I_0. The thrust values were taken from the wind turbine data for the wind speed of 8 m/s.

The turbulence intensity for an ambient wind speed of 8 m/s was calculated also for the Middelgrunden wind farm with the Frandsen and our model.

In figure 7 the turbulence intensity for each wind turbine could be seen. The values from our model are weighted with the wind direction probability and the model from Frandsen is rated for all wind directions.

The Frandsen model is about 50% higher than the values from our model. At both models the turbulence intensity is lower at the second and the last but one wind turbine. Our model gives nearly the same turbulence intensity value for all middle wind turbines. The model from Frandsen includes a second step in turbulence intensity, caused by the use of the wind farm roughness corrected ambient turbulence for the wind turbines inside the wind farm.

The fact that the turbulence intensity from the Frandsen model is higher than the values predicted from our model might result from the wind direction weighted calculation of the turbulence intensity, used with our model, which gives the main wind direction perpendicular to the axis of the wind farm more influence on the turbulence intensity level. For better comparison we work on a solution to use the Frandsen model with wind direction distribution.

7. CONCLUSION

A new model for the turbulence intensity inside wind farms was developed and used to offshore wind farms.

The model is compared with horizontal turbulence intensity profiles from the Vindeby offshore wind farm. The calculated profiles agree very well with the model. Both the maximum value and the nearly symmetric shape of the measured profiles, which results from the homogenous surrounding of the wind farm were modelled accurately.

The model was applied to calculate the rotor averaged turbulence intensity for the 20 turbines at Middelgrunden wind farm for two wind direction cases. The results were compared with the turbulence intensities derived by Jørgensen from measured power fluctuations.

Our model shows an overestimation of the turbulence intensities inside Middelgrunden wind farm. The method from Jøergensen to derive the turbulence intensity from the standard deviation of power measurement might have the disadvantage that only turbulent structures in the size of the rotor diameter have influence on these power fluctuations. If the size of the turbulent structures is decreasing in multiple wakes, the derived turbulence intensities would be too low. It has to be investigated if the deviations between model and measurement are due to shortcomings in the model of multiple wakes or due to uncertainties in the derivation of the measured values.

The comparison to the Frandsen model shows that the model derives higher values for the turbulence intensity at the wind turbines than our does. The Frandsen model is not direct comparable with our model, as it calculates the effective turbulence intensity, which might differ from the meteorological turbulence intensity.

Interesting is the fact that the turbulence intensities calculated from our model differ minimal between the wind turbines inside the wind farm, which results due to the influence of the main wind direction, which allows a free stream situation on all wind turbines.

In the future a wind direction depending turbulence intensity should eliminate smaller differences between measured and simulated profile. Also better comparison with a wind direction depending Frandsen model should be done in future.

8. Acknowledgements

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